TECHNICAL NOTE

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COMPARISON OF HYDRAZINE - NITROGEN TETROXIDE AND HYDRAZINE - CHLORINE TRIFLUORIDE IN SMALL-SCALE ROCKET CHAMBERS

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SUMMARY

The performance potentials of hydrazine - nitrogen tetroxide and hydrazine - chlorine trifluoride were compared in nominal 300-pound-thrust uncooled rocket engines. Triplet, shower-head, like-on-like, and swirl-cup injectors were used. Data are presented for characteristic exhaust velocity as a function of weight percent fuel flow.

Similar injectors gave greater characteristic exhaust velocities with hydrazine - nitrogen tetroxide than with hydrazine - chlorine trifluoride. With either propellant combination the triplet injector gave the best performance. The maximum performance of the hydrazine - nitrogen tetroxide combination with the 60°-impingement-angle triplet was 5790 feet per second at 50 percent fuel by weight. With hydrazine - chlorine trifluoride the 30°-impingement-angle triplet gave a maximum performance of 5450 feet per second at 34 weight percent fuel. The swirl cup gave 97 percent of the theoretical characteristic exhaust velocity with hydrazine - nitrogen tetroxide. The shower-head and like-on-like injectors gave substantially lower performance with both combinations.

In none of the runs was there any corrosion or erosion of the injectors, either from the propellants or combustion heat flux. There were no problems with hydrazine decomposition or in rocket starting.

INTRODUCTION

A need exists for a propellant combination for upper-stage propulsion and control in space vehicles that can be stored without loss under varying conditions for considerable time. It is conceivable that high-energy cryogenic propellants can be stored in open space where convection is not a factor and where radiation from higher temperature bodies is small enough to be effectively reflected. However, in the immediate vicinity of planets, both convective and radiative heat transfer may be such as to cause considerable loss of cryogenic propellants. Under these conditions, a propellant combination with low vapor pressures at terrestrial temperatures would have considerable advantages even though its specific impulse was lower than that for the cryogenics. Ideally, such a propellant combination should have high specific impulse, high density, and high cooling capacity and should be hypergolic.

Two combinations which each offer a good combination of these characteristics are hydrazine with nitrogen tetroxide and hydrazine with chlorine trifluoride. Both offer good, though not outstanding, theoretical performance. (Chlorine trifluoride is equivalent to liquid oxygen - RP1; nitrogen tetroxide is 1 percent less.) Both are hypergolic. Both are dense; the bulk specific gravity for hydrazine - chlorine trifluoride is 1.55; for hydrazine - nitrogen tetroxide it is 1.27 at peak performance compositions. Both offer good cooling capacity, with hydrazine - nitrogen tetroxide having the edge because of higher fuel flow. Other properties of these propellants can be found in table I.

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In the past 10 years small-scale studies with hydrazine - chlorine trifluoride have been done at NACA, North American Aviation, Inc., M. W. Kellogg Co., and Jet Propulsion Laboratory. These were done in order to determine performance with various injector designs and to investigate operational problems. During the past 5 years JPL has also done basic heat-transfer studies with the three propellants discussed herein. Experimental rocket studies of the same nature with hydrazine and nitrogen tetroxide have been and are being done at JPL.

The work reported herein compares the performance of two competitive combinations with identical injectors. This report also investigates the injector principles and techniques necessary to achieve high characteristic exhaust velocity efficiency with these combinations. Both combinations are reactive in the liquid phase; therefore, energy may be available for improving vaporization and atomization during the injection process, which should improve over-all engine efficiency. This energy may best be utilized by using injectors which promote rapid and thorough liquid phase mixing, such as triplet and swirl-cup types (ref. 1).

Tests were made in uncooled combustion chambers at a nominal thrust of 300 pounds and a chamber pressure of 300 pounds per square inch absolute. The injectors used included shower-head, triplet, like-on-like, and swirl-cup types. In all tests, the hydrazine was preheated to 200° F to simulate the output from the cooling passages of a regenerative engine. Experimental characteristic exhaust velocity is shown as a function of percent fuel concentration for each combination. The data for both combinations are compared with each other and the theoretical values.

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APPARATUS

Propellants

Liquid hydrazine was obtained from an industrial supplier in glass, aluminum, and stainless-steel containers. NASA laboratory analysis showed that the hydrazine was 98.4 percent pure, the remainder being water and a trace of ammonia. The nitrogen tetroxide arrived from the supplier in 125-pound-capacity steel cylinders. The specifications indicated it to be at least $99\frac{1}{2}$ percent pure nitrogen tetroxide plus 1/2 percent water and nitrosyl chloride (NOCl). The chlorine trifluoride was purchased from the supplier in 5-pound-capacity gas cylinders. The purity of the contents is 99 percent or greater with the remaining gases being free chlorine or fluorine or both.

Propellant System

A flow diagram of the system used in making this investigation is shown in figure 1. The oxidant system consisted of a 1/3-cubic-foot monel tank from which either the nitrogen tetroxide or chlorine trifluoride flowed to the injector through a stainless-steel line, a flowmeter, and a fire valve. The entire system was in a constant-temperature bath of cold water. A stainless-steel flow line, a flowmeter, and a fire valve were between the 1/4-cubic-foot stainless-steel fuel tank and the injector. The fuel tank containing the hydrazine was submerged in a heated water bath.

Instrumentation

The oxidant and fuel flowmeters were turbine-type meters, and the signal from each was recorded on a cycle totalizer, a recording self-balancing potentiometer strip chart, and an oscillograph. The temperatures of both the oxidant and fuel at the flowmeters were measured with thermocouples and were recorded on self-balancing potentiometer strip charts. The fuel inlet temperature to the injector and the chamber outside wall temperature were measured and recorded in the same manner. The engine chamber pressure was measured by a strain-gage pressure transducer recording on the oscillograph and by a Bourdon-tube recording on a strip chart recorder. The accuracy of the calculated performance data based on reading error and instrument and indicator inaccuracy was about ±2.5 percent.

Injectors

The injectors used in this program are shown in figure 2. The two triplets, the like-on-like, and the shower-head injector consisted of nine independent elements. Each element consisted of an axial oxidant jet of 0.043-inch diameter together with two or more fuel jets. The diameter of the fuel jets was 0.025 inch for the triplets when used for the hydrazine - chlorine trifluoride tests and about 0.03 inch when used for the hydrazine - nitrogen tetroxide tests. The shower-head and like-on-like fuel jets were 0.021 inch in diameter[1]. The two triplet injectors differed only in that the fuel jets for one impinged on the oxidant jet at an included angle of 30°, and for the other injector the angle was 60°. The impingement distance perpendicular to the face was 0.578 inch for the 30° triplet, 0.265 inch for the 60° triplet, and 0.203 inch for the fuel like-on-like. For these four injectors a distribution plate directly beneath the faceplate channeled the fuel flow so that the face was kept cool. The oxidant jet rods and faceplates of these injectors were made of copper for better face cooling. The rest of the injector was made of stainless steel. The parts were furnace-brazed together.

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The swirl-cup injector was made from one piece of copper. The hydrazine entered the cup at two ports 180° apart tangent to the cup wall and 80° from an axial line through the cup. The nitrogen tetroxide was inserted into the cup from two 0.09-inch-diameter holes each 90° from the fuel ports and at the same angle with the cup axial centerline as the fuel. Several cup diameters and depths were tried. An error in machining resulted in the cup depth extending upstream of the fuel and oxidant ports. This produced a void upstream of the fuel and oxidant entries. Attempts were made to press fit plugs into this void but the plugs could not be kept in during a run.

Thrust Chambers

The thrust chambers were made of $2\frac{1}{2}$-inch-diameter copper or steel pipe with 1/4-inch-thick walls. They were all 8 inches long and had a characteristic length of 32 inches. The nozzles, which were solid copper with no divergent section, had a throat diameter of approximately 0.93 inch.

PROCEDURE

Both the fuel and oxidant propellant systems were first pressure checked. Next, the oxidant tank bath and flow line trough were filled with cold water, and the oxidant tank weighing apparatus was calibrated. In order to transfer oxidant from the commercial supply tank into the oxidant tank, the vapor pressure of the oxidant was utilized. The

[1]The like-on-like injector was a hybrid in that only the fuel jets impinged in a like-on-like pattern. The oxidant jets were nonimpinging; i.e., they were in a shower-head configuration.

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vapor pressure supply source, which was at ambient temperature, was higher than that in the cold oxidant tank; thus, the pressure forced the oxidants through a dip-tube transfer line into the oxidant tank. In the oxidant tank the chlorine trifluoride temperatures were 36° to 40° F; nitrogen tetroxide temperatures were 42° to 58° F. Hydrazine, after being put in the fuel tank, was warmed to about 200° F. Both propellant tanks were pressurized with helium gas. Propellant flow was varied by changes in tank pressure. Fuel and oxidant were introduced into the rocket simultaneously. Ignition was spontaneous for both combinations, and stable combustion conditions were achieved within 1 second. Most of the runs were of 3 to 4 seconds in duration. After each run the injector and flow lines were purged with helium. The injector, chamber, and nozzle were checked for corrosion, erosion, burning, or distortion after each series of runs.

Characteristic exhaust velocity was calculated from the experimentally determined values of chamber pressure and total propellant flow during stable portions of each run.

RESULTS

Experimental data and results are presented in tables II and III and figures 3, 4, and 5. Table II lists all the data necessary to calculate the performance of each of the injectors tested with hydrazine - chlorine trifluoride (N_2H_4-ClF_3), and table III lists data for hydrazine - nitrogen tetroxide (N_2H_4-N_2O_4). Characteristic exhaust velocity C^* is shown as a function of percent fuel for each of the injectors in figure 3 (N_2H_4-ClF_3 tests) and figure 4 (N_2H_4-N_2O_4 tests). The broken lines indicate various levels of theoretical performance as a function of weight percent fuel. Faired curves (solid) were drawn through the performance points for each of the injectors. The faired curves from figures 3 and 4 are shown together in figure 5 in order to compare results.

Hydrazine - Chlorine Trifluoride

The 30°-impingement-angle triplet injector gave the highest performance. As shown in figure 3 the characteristic exhaust velocity peaked at 5450 feet per second (93 percent of theoretical equilibrium performance) at a fuel flow of 31 percent by weight. Just below it in performance was the 60°-impingement-angle triplet injector. Its performance was a maximum at a fuel flow of about $34\frac{1}{2}$ percent by weight and a characteristic exhaust velocity of 5390 feet per second (92 percent of theoretical). The maximum C^* of the shower-head injector was even further in the fuel-rich region; a fuel flow of approximately 40 percent by weight gave 4970 feet per second (86 percent of theoretical). A limited number of tests were made with the like-on-like injector which indicated its performance was even lower than that of the shower-head injector, that is, less than 85 percent of theoretical at the greatest C^* obtained.

Hydrazine - Nitrogen Tetroxide

The 60°-impingement-angle triplet injector gave the highest C^* for this combination (see fig. 4). The curve peaked at about 5790 feet per second, which is 99 percent of theoretical equilibrium performance at a fuel flow of 49 weight percent. The other triplet injector's performance was just below this: 5750 feet per second (98 percent of theoretical) at a fuel flow of 52 percent by weight. Swirl-cup-injector performance peaked at a fuel flow of 49 weight percent. Characteristic exhaust velocity was 5690 feet per second (97 percent of theoretical) at that oxidant-fuel ratio. A definite peak was never realized with the like-on-like injector. At a 44-weight-percent fuel flow, its characteristic exhaust velocity was 4700 feet per second. As the propellant mixture became increasingly fuel rich, the characteristic exhaust velocity increased erratically and reached a high value of 5600 feet per second at a fuel flow of 67 weight percent.

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Operational Conditions

No hard starts were noted in any of the runs. Rough combustion was apparent only with the swirl-cup injectors. This roughness was evidently due to a mistake in fabrication. The cup being deeper than the propellant inlets resulted in a void in which some of the propellant was apparently reacting and ejecting the main propellant mass from the cup.

A thermocouple in the side of the uncooled chamber indicated the outside wall was usually at about 1200° F for a 3- to 4-second run and often exceeded 1800° F when the performance was high. Such temperatures resulted in the chamber walls ballooning out, but not rupturing, before the test could be terminated.

Inspection of each injector after running showed no erosion or corrosion. Slimy deposits were noted on the injector faces after the hydrazine - chlorine trifluoride runs.

DISCUSSION

Thermochemical calculations indicate slightly higher theoretical performance with hydrazine - chlorine trifluoride than with hydrazine - nitrogen tetroxide. However, results of this investigation showed that with the same injector substantially higher performance could be obtained with hydrazine - nitrogen tetroxide. The performance of the triplets and swirl-cup injectors seemed much less sensitive to mixture ratio and more closely approached theoretical performance with hydrazine - nitrogen tetroxide than with hydrazine - chlorine trifluoride.

The performance curves obtained with hydrazine - chlorine trifluoride resemble curves obtained for similar injectors with nonhypergolic propellants (ref. 2). When propellant reaction in the liquid phase is negligible, aerothermodynamic vaporization of atomized droplets may be considered as controlling combustion efficiency. This has been shown for heptane-oxygen and appears to be the case for hydrazine - chlorine trifluoride.

The performance curves for nitrogen tetroxide, however, indicated a significant increase over the performance expected with normal aerothermodynamic vaporization when liquid mixing was emphasized (i.e., triplet and swirl-cup injectors). The like-on-like fuel (shower-head oxidant) injector, which was not designed for liquid phase mixing, fell well below the other injectors in performance. However, with increasing fuel richness, the characteristic velocity increased erratically. At a fuel flow of about 60 percent its efficiency was equivalent to the other injectors. This would indicate that liquid phase reaction may have been occurring sporadically as the over-all fuel turbulence increased. The general performance level for this injector with hydrazine - chlorine trifluoride was very low and did not show the same steep increase with percent fuel.

These results apparently indicate that liquid phase reactions with hydrazine - chlorine trifluoride are not as rapid or vigorous as with hydrazine - nitrogen tetroxide. This may be due in part to the dissociation of nitrogen tetroxide (N_2O_4 + heat $\rightarrow 2NO_2$, which is 90 percent complete at 200° F). The generation of nitrogen dioxide can enhance propellant vaporization and reaction. Chlorine trifluoride does not have this advantage.

SUMMARY OF RESULTS

The performance of hydrazine - nitrogen tetroxide and hydrazine - chlorine trifluoride was studied experimentally in a nominal 300-pound-thrust uncooled rocket engine at 300 pounds per square inch absolute. The propellant mixture ranged from 36 to 75 percent fuel by weight for hydrazine - nitrogen tetroxide and from 24 to 50 percent fuel by weight for hydrazine - chlorine trifluoride. Triplet, swirl-cup, shower-head, and like-on-like injectors were used. The following results were obtained:

1. All the injectors gave greater characteristic exhaust velocities with hydrazine - nitrogen tetroxide than with hydrazine - chlorine trifluoride.

2. With either propellant combination the triplet injectors gave the highest performance. The maximum performance of the 60°-impingement-angle triplet was 5790 feet per second with hydrazine - nitrogen tetroxide at 50 percent fuel by weight. With hydrazine - chlorine trifluoride the 30°-impingement-angle triplet gave a maximum performance of 5450 feet per second at 34 percent fuel by weight.

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3. The performance of hydrazine - chlorine trifluoride seemed more dependent on injector type than did hydrazine - nitrogen tetroxide.

4. There was no problem in cooling the injector face during any run with either combination.

5. No corrosion or metal erosion was apparent with any of the propellants. Hydrazine decomposition was insignificant. There were no difficulties in starting with either propellant combination.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, August 4, 1959

REFERENCES

1. Hartridge, H., and Roughton, F. J. W.: A Method of Measuring the Velocity of Very Rapid Chemical Reactions. Proc. Roy. Soc. (London), ser. A, vol. CIV, no. A726, Oct. 1, 1923, p. 379.

2. Heidmann, M. F., and Auble, C. M.: Injection Principles from Combustion Studies in a 200-Pound-Thrust Rocket Engine Using Liquid Oxygen and Heptane. NACA RM E55C22, 1955.

TABLE I. - PROPERTIES OF ROCKET PROPELLANTS

	Hydrazine	Chlorine trifluoride	Nitrogen tetroxide
Formula	N_2H_4	ClF_3	$2NO_2 \rightleftarrows N_2O_4$
Molecular weight	32.1	92.5	46 $\rightleftarrows$ 92
Density, lb/cu ft, at 70° F	63.1	113.5	90.3
Vapor pressure, lb/sq in. abs, at 70° F	0.29	21.5	14.8
Melting point, °F	34	-117	11.8
Boiling point, °F, at 1 atm	236	54	69.8

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TABLE II. - EXPERIMENTAL PERFORMANCE OF LIQUID HYDRAZINE AND CHLORINE TRIFLUORIDE

Fuel flow, percent	Total propellant flow, lb/sec	Fuel temperature, °F	Chamber pressure, lb/sq in. abs	Characteristic velocity, C*, ft/sec
Fuel like-on-like (oxidant shower-head) injector				
29.8	1.38	180	274	4395
31.7	1.36	175	274	4460
32.1	1.47	195	288	4340
32.3	1.45	190	286	4380
43.3	1.21	155	260	4785
Shower-head injector				
25.3	1.22	158	243	4370
26.8	1.22	162	247	4450
28.6	1.21	168	263	4770
28.7	1.08	190	222	4410
29.1	1.17	190	236	4320
32.8	1.22	172	266	4800
35.4	1.36	205	305	5000
35.5	1.21	180	282	5110
36.4	1.31	205	293	4990
36.6	1.32	210	292	4960
38.4	1.26	210	290	5160
39.2	1.37	200	304	4960
39.7	1.38	205	309	4980
40.6	1.15	190	261	4880
41.5	1.25	210	277	4920
41.6	1.36	195	304	5000
44.7	1.11	190	254	4920
49.1	1.17	165	268	4935
50.2	1.21	155	282	5010
Triplet injector, 60° impingement angle				
24.6	1.38	205	292	4730
27.3	1.35	200	300	4960
27.6	1.35	195	309	5100
31.1	1.36	185	317	5210
34.6	1.34	175	318	5290
35.4	1.33	205	323	5440
39.9	1.29	160	295	5110
Triplet injector, 30° impingement angle				
25.1	1.30	200	310	5250
25.2	1.36	185	323	5260
27.1	1.28	195	314	5390
28.5	1.34	195	329	5450
30.6	1.34	200	329	5450
31.3	1.24	195	310	5490
33.4	1.28	205	310	5330
34.3	1.30	205	320	5440
35.0	1.35	205	324	5340
37.3	1.26	200	311	5430
37.9	1.28	205	309	5340
38.5	1.32	205	327	5460
39.7	1.32	205	321	5400

TABLE III. - EXPERIMENTAL PERFORMANCE OF LIQUID HYDRAZINE AND NITROGEN TETROXIDE

Fuel flow, percent	Total propellant flow, lb/sec	Fuel temperature, °F	Chamber pressure, lb/sq in. abs	Characteristic velocity, c*, ft/sec
Fuel like-on-like (oxidant shower-head) injector				
43.9	1.31	82	281	4740
44.2	1.37	104	293	4700
46.9	1.32	66	288	4810
48.5	1.30	178	290	4900
48.7	1.36	193	327	5290
51.7	1.32	170	303	5050
52.3	1.33	188	332	5490
54.2	1.32	164	305	5080
56.4	1.28	116	313	5380
58.4	1.30	184	327	5560
61.6	1.28	177	323	5580
66.8	1.25	167	319	5610
Swirl-cup injector				
43.9	1.02	140	262	5620
44.1	.80	188	208	5710
45.3	1.11	198	292	5640
47.2	1.14	198	294	5650
49.9	.92	134	244	5820
51.8	1.12	198	284	5580
53.5	.82	180	206	5510
55.7	1.07	200	273	5590
61.2	1.02	200	259	5570
66.3	1.01	200	244	5310
75.2	.96	200	225	5170
Triplet injector, 60° impingement angle				
36.5	1.22	200	309	5580
39.4	1.23	200	317	5700
41.9	1.22	200	313	5640
45.6	1.25	200	328	5790
46.8	1.22	198	314	5680
47.5	1.20	158	322	5880
49.4	1.25	202	330	5820
52.1	1.22	164	311	5600
53.9	1.27	202	326	5660
54.5	1.25	202	330	5810
56.9	1.25	172	318	5600
57.1	1.33	202	340	5650
59.9	1.38	202	345	5530
61.7	1.36	146	330	5350
Triplet injector, 30° impingement angle				
38.3	1.33	96	321	5310
39.5	1.31	68	320	5380
41.4	1.25	185	317	5600
42.1	1.26	58	315	5560
44.7	1.26	80	320	5590
44.8	1.29	180	328	5590
46.6	1.24	198	317	5610
49.0	1.27	48	328	5680
51.1	1.20	190	316	5790
52.7	1.21	176	319	5820
53.0	1.28	188	328	5650
58.0	1.24	176	315	5580
58.9	1.24	168	310	5530
60.1	1.27	160	321	5560
60.2	1.28	160	326	5630
65.7	1.34	142	317	5190
72.0	1.35	132	307	4990

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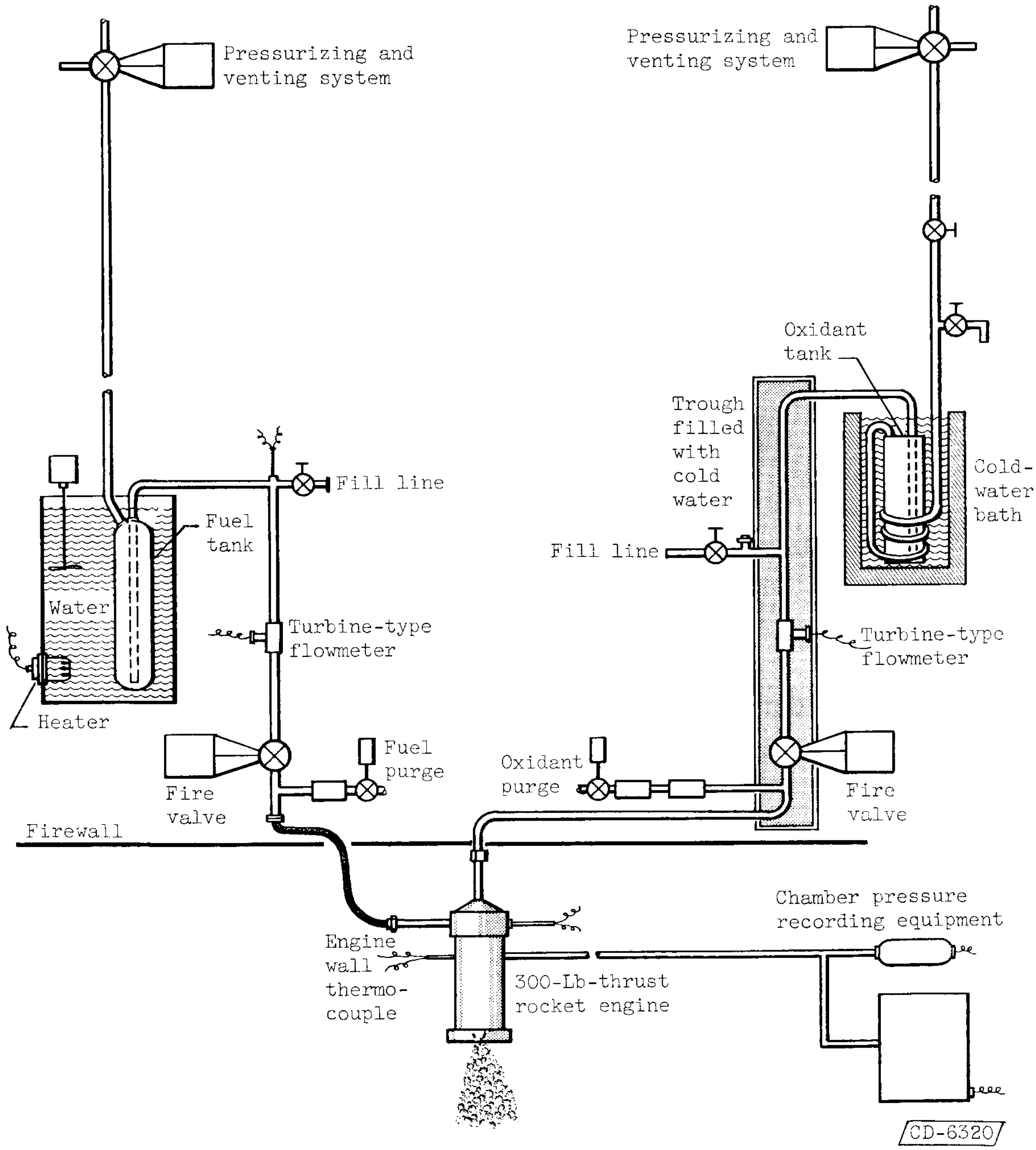

Figure 1. - Flow diagram of propellant system.

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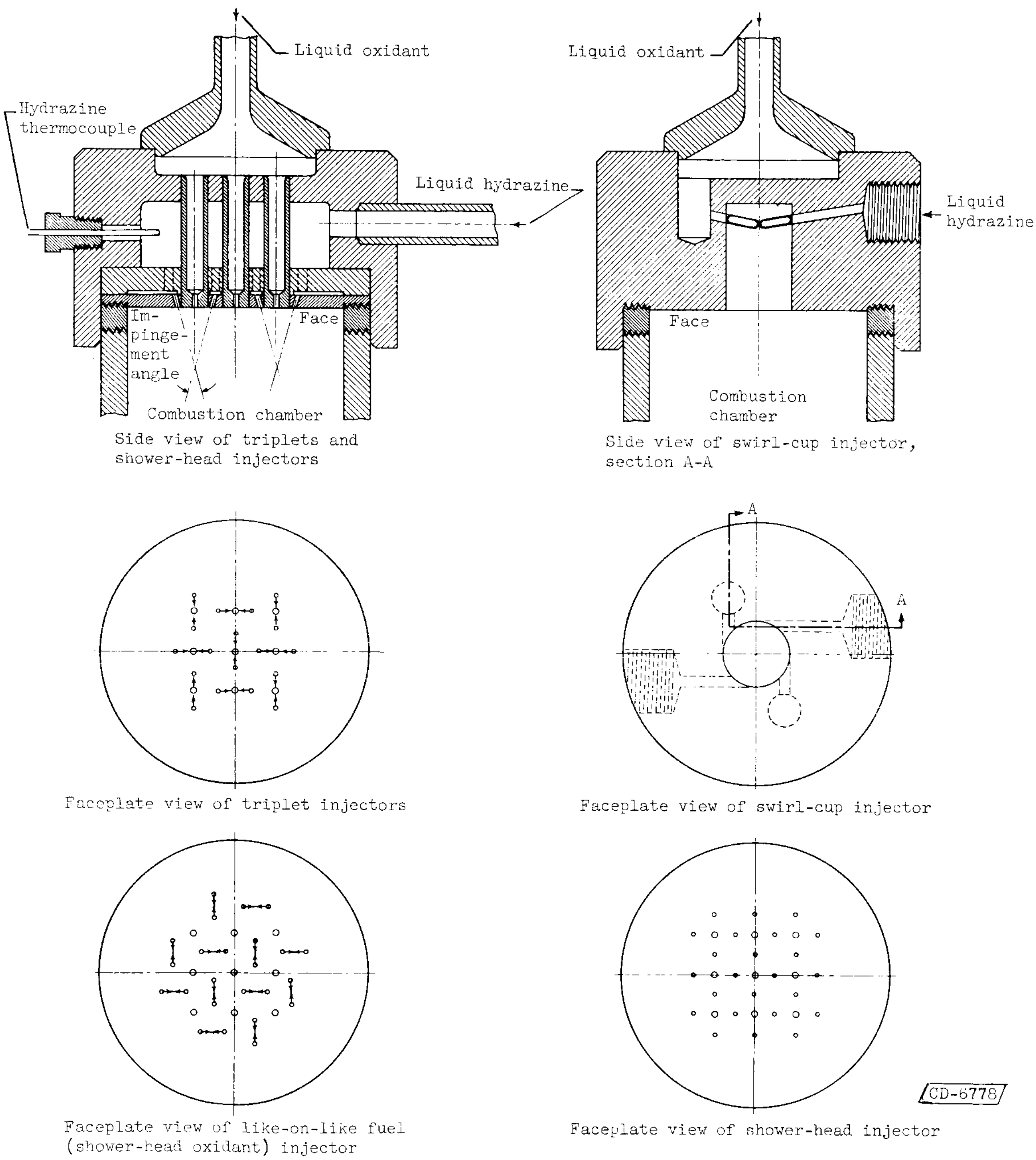

Figure 2. - Injector designs.

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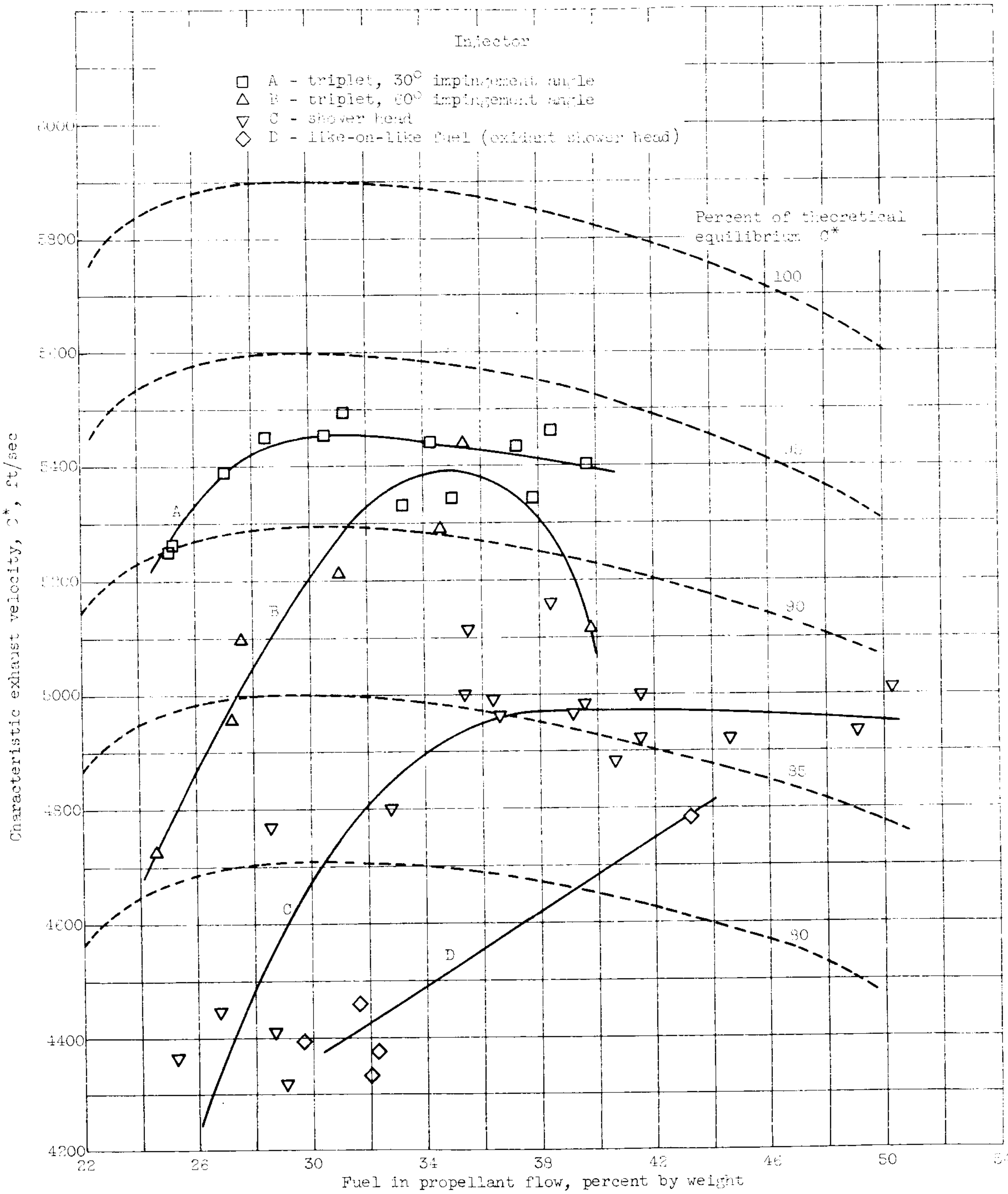

Figure 3. - Theoretical and experimental characteristic exhaust velocity of liquid hydrazine - liquid chlorine trifluoride in 300-pound-thrust engines at chamber pressure of 300 pounds per square inch absolute.

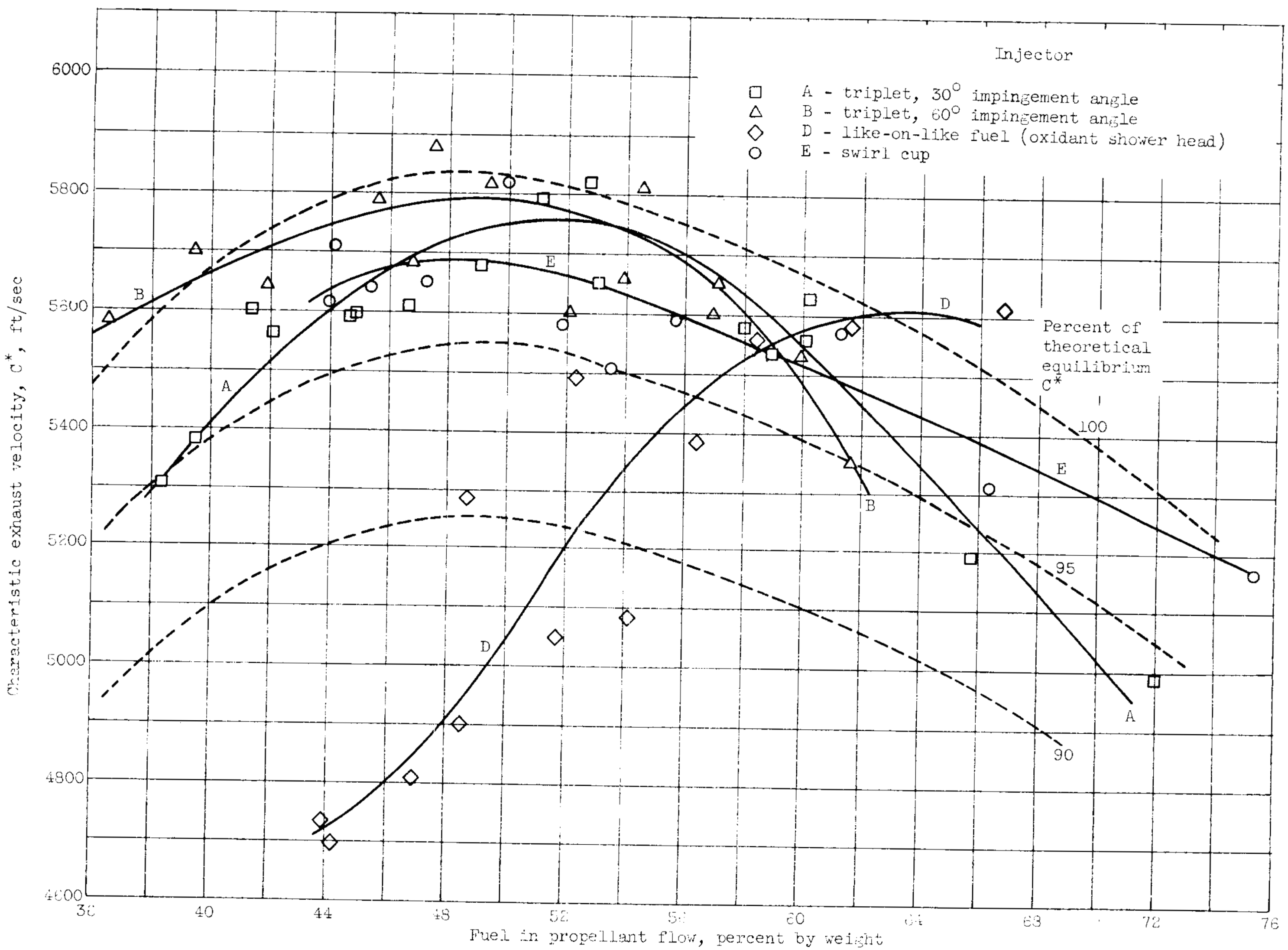

Figure 4. - Theoretical and experimental characteristic exhaust velocity of liquid hydrazine - liquid nitrogen tetroxide in 300-pound-thrust engines at chamber pressure of 300 pounds per square inch absolute.

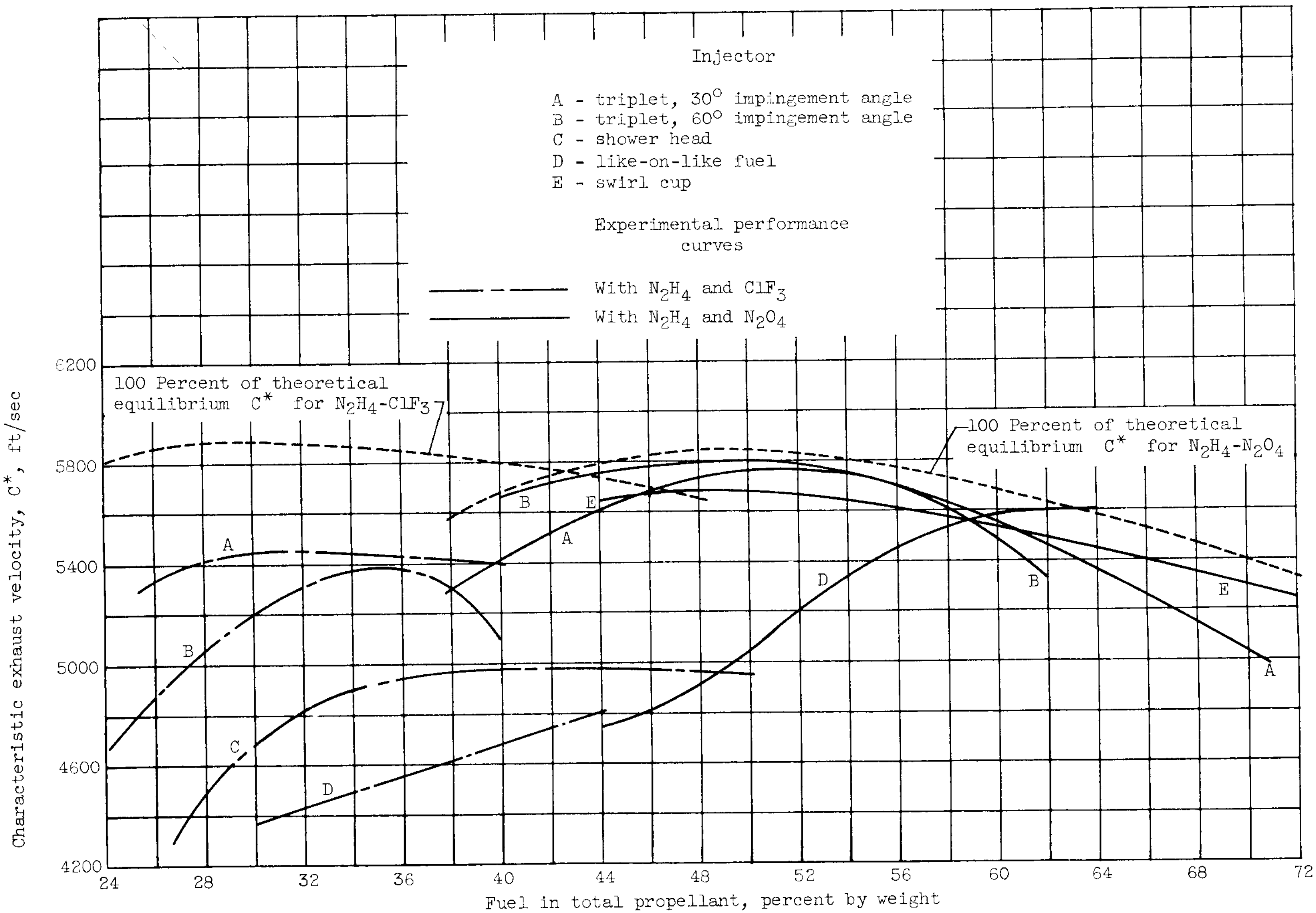

Figure 5. - Comparison of theoretical and experimental characteristic exhaust velocities of liquid hydrazine - liquid chlorine trifluoride and liquid hydrazine - liquid nitrogen tetroxide in 300-pound-thrust engines at chamber pressure of 300 pounds per square inch absolute.

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